AD-A131 572 RISING BUBBLES(U) STANFORD UNIV CA DEPT OF MATHEMATICS 1/1
J B KELLER DEC 82 AFOSR-TR-83-0676 AFOSR-79-0134

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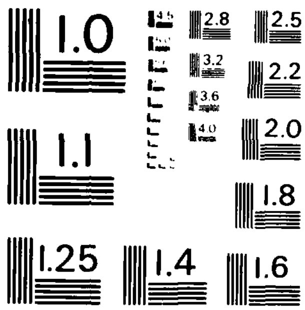


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# REPORT DOCUMENTATION PAGE

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| | | |
|---|---|---|
| 1. REPORT NUMBER: AFOSR-TR- 83-0676 | 2. GOVT ACCESSION NO.: AD-A131572 | 3. RECIPIENT'S CATALOG NUMBER |
| 4. TITLE (and Subtitle): "RISING BUBBLES" | | 5. TYPE OF REPORT & PERIOD COVERED: INTERIM |
| | | 6. PERFORMING ORG. REPORT NUMBER |
| 7. AUTHOR(s): Joseph B. Keller | | 8. CONTRACT OR GRANT NUMBER(s): AFOSR-79-0134 |
| 9. PERFORMING ORGANIZATION NAME AND ADDRESS: Stanford University, Stanford, CA 94305 | | 10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS: PE61102F; 2304/A4 |
| 11. CONTROLLING OFFICE NAME AND ADDRESS: AFOSR/NM, Bldg. 410, Bolling AFB DC 20332 | | 12. REPORT DATE: Dec 1982 |
| | | 13. NUMBER OF PAGES: 16 |
| 14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office) | | 15. SECURITY CLASS. (of this report): UNCLASSIFIED |
| | | 15a. DECLASSIFICATION DOWNGRADING SCHEDULE |

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

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19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)


This is a progress report of the Applied Mathematics Group in the Mathematics Department, Stanford University. This report lists publications supported by AFOSR through March 16, 1982 - December 31, 1982.


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AFOSR-TR- 83-0676

"Rising Bubbles"

PROGRESS REPORT

March 16, 1982 - December 31, 1982

Applied Mathematics Group
Department of Mathematics
Stanford University

Principal Investigator: Joseph B. Keller



## I. Introduction

This is a progress report of the Applied Mathematics Group in the Mathematics Department, Stanford University. This group began functioning officially on September 1, 1979, and is supported by:

1. Office of Naval Research;
2. National Science Foundation;
3. Army Research Office;
4. Air Force Office of Scientific Research;
5. Stanford University.

The personnel comprising this group during all or part of the reporting period are:

1. Joseph B. Keller, Professor of Mathematics, Stanford University;
2. Russel E. Caflisch, Assistant Professor, Stanford University;
3. John C. Neu, Assistant Professor, Stanford University;
4. Victor Twersky, Professor of Mathematics, University of Illinois, Chicago Circle;
5. John G. Watson, Assistant Professor, University of Miami;
6. Bernard A. Lippmann, Professor of Physics, Emeritus, New York University;
7. Si-Xiong Chen, Head, Applied Mathematics Group, Institute of Mechanics, Beijing, People's Republic of China;
8. Meira Falkovitz, Postdoctoral Fellow, Stanford University;

9. John H. Maddocks, Postdoctoral Fellow, Stanford University;

10. Allan D. Jepson, Postdoctoral Fellow, Stanford University;

11. Kevin C. Nunan, Graduate Student;

12. Michael I. Weinstein, Postdoctoral Fellow, Stanford University;

13. Stephanos Venakides, Assistant Professor, Stanford University;

14. Margaret Cheney, Research Associate, Stanford University;

15. Graham Eatwell, Postdoctoral Fellow, Stanford University;

16. Luis Bonilla, Research Associate, Stanford University;

17. James Geer, Professor of Mathematics, School of Advanced Studies, SUNY, Binghampton, New York.

The various research activities of the members of this group are indicated by the list of publications contained in Section II. Abstracts or introductions from the papers produced during the report period are contained in Section III.

In addition to the manuscripts already submitted, a number of projects are nearing completion. Thus Professor Keller, while at the Woods Hole Oceanographic Institute during the summer of 1982, studied the turbulent diffusion of a chemically reacting substance. Professor Keller and Dr. Falkovitz are completing a paper on Liesegang rings to account for the recent results of John Ross and his co-worker in the Chemistry Department at Stanford. Their theory uses the fourth order Cahn-Hilliard equation to describe diffusion. Dr. Eatwell is studying the propagation of an acoustic wave through a bubbly fluid, or through a medium containing resonant scatterers. Dr. Bonilla is studying the effective behavior of an elastic solid composed of randomly oriented crystallites. Mr. Nunan is calculating the effective viscosity of a suspension of rigid spherical particles in a viscous fluid. Professors Geer and Keller are studying scattering of waves by thin bodies.

In December, Professor Keller was invited to deliver the Weizmann Lectures at the Weizmann Institute of Science in Rohovot, Israel.

## II. PUBLICATIONS OF APPLIED MATHEMATICS GROUP

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| 1. | J. B. Keller | Training in applied mathematics<br>Pub: Proc. of the Conf. on Graduate Training in Math., T. L. Sherman, ed., Rocky Mountain Mathematics Consortium, Tempe, Arizona, 1979, pp. 110-113. |
| 2. | J.-M. Vanden-Broeck<br>L. W. Schwartz | Numerical computation of steep gravity waves in shallow water<br>Pub: Phys. Fluids, 22, 1868-1871, 1979. |
| 3. | H. McMaken<br>J. D. Achenbach<br>L. Adler<br>D. K. Lewis | Diffraction of ultrasonic waves by penny-shaped cracks in metals: Theory and experiment<br>Pub: J. Acoust. Soc. Am., 66, 1848-1856, 1979. |
| 4. | J.-M. Vanden-Broeck<br>J. B. Keller | A new family of capillary waves<br>Pub: J. Fluid Mech., 98, 161-169, 1980. |
| 5. | J.-M. Vanden-Broeck | Nonlinear stern waves<br>Pub: J. Fluid Mech., 93, 603-611, 1980. |
| 6. | J. B. Keller | Plate failure under pressure<br>Pub: SIAM Rev., 22, 227-228, 1980. |
| 7. | J.-M. Vanden-Broeck | Advances in the numerical computation of capillary-gravity waves<br>Pub: Nonlinear Partial Differential Equations in Engineering and Applied Science, R. L. Sternberg, A. J. Kalinowski and J. S. Papadakis, eds., Marcel Dekker, New York, 1980, pp. 299-310. |
| 8.* | S. Childress<br>J. B. Keller | Lichen growth<br>Pub: J. Theor. Biol., 82, 157-163, 1980. |
| 9. | J. B. Keller | Liesegang rings and a theory of fast reaction and slow diffusion<br>Pub: Dynamics and Modelling of Reactive Systems, W. Stewart, ed., Academic, New York, 1980, pp. 211-224. |

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10. J. B. Keller — Darcy's law for flow in porous media and the two-space method

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11. R. E. Caflisch — The Boltzmann equation with a soft potential, Part I: Linear, spatially-homogeneous

Pub: Comm. Math. Phys., 74, 71-95, 1980.

12. R. E. Caflisch — The Boltzmann equation with a soft potential, Part II: Nonlinear, spatially-periodic

Pub: Comm. Math. Phys., 74, 97-109, 1980.

13. J. C. Neu — The method of near identity transformations and applications

Pub: SIAM J. Appl. Math., 38, 189-208, 1980.

14. J. C. Neu — Large populations of chemical oscillators

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15. J. B. Keller, M. Miksis — Bubble oscillations of large amplitude

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16. J.-M. Vanden-Broeck, J. B. Keller — Bubble or drop distortion in a straining flow in two dimensions

Pub: Phys. Fluids, 23, 1491-1495, 1980.

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Pub: SIAM Rev., 22, 442-458, 1980.

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Pub: J. Fluid Mech., 101, 673-686, 1980.

19. J.-M. Vanden-Broeck — Nonlinear gravity-capillary stern waves

Pub: Phys. Fluids, 23, 1949-1953, 1980.

20. R. E. Caflisch — An inverse problem for Toeplitz matrices and the synthesis of discrete transmission lines

Pub: J. Linear Algebra and Its Applications, 38, 255-272, 1980.

21. R. E. Caflisch — The fluid dynamic limit of the nonlinear Boltzmann equation

Pub: Comm. Pure Appl. Math., 33, 651-666, 1980.

22.* J. B. Keller — Tendril shape and lichen growth

Pub: Some Mathematical Questions in Biology, Lectures on Math. in the Life Sciences, Vol. 13, Am. Math. Soc., Providence, 1980, pp. 257-274.

23.* R. E. Caflisch, C. Peskin, G. Majda, G. Strumolo — Distortion of the arterial pulse

Pub: Math. Bio. Sci., 51, 229-260, 1980.

24.* P. S. Hagan, H. Simpson, D. S. Cohen — Spatial structures in predator-prey communities with hereditary effects and diffusion

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26. J.-M. Vanden-Broeck — Two-dimensional drops in slow viscous flow

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29. J. B. Keller — Temperley's model of gas condensation

<u>Pub</u>: J. Chem. Phys., <u>74</u>, 4203-4204, 1981.

30. J. B. Keller, J. G. Watson — Kelvin wave production

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33. J.-M. Vanden-Broeck — Numerical calculation of standing waves in water of arbitrary uniform depth

<u>Pub</u>: Phys. Fluids, <u>24</u>, 812-815, 1981.

34. R. E. Caflisch, K. C. Nunan — Evaluation of a function at infinity from its power series

<u>Pub</u>: Phys. Rev. Letters, <u>46</u>, 1255-1256, 1981.

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36. R. E. Caflisch, J. B. Keller — Quench front propagation

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| 40. | R. Burridge<br>J. B. Keller | Poroelasticity equations derived from microstructure<br><br>Pub: J. Acoust. Soc. Am., 70, 1140-1146, 1981. |
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| 42. | M. J. Miksis | Shape of a drop in an electric field<br><br>Pub: Phys. Fluids, 24, 1967-1972, 1981. |
| 43. | J.-M. Vanden-Broeck | The influence of capillarity on cavitating flow past a flat plate<br><br>Pub: Quart. J. Mech. Appl. Math., 34, 465-473, 1981. |
| 44. | A. Jeffrey<br>J. Mvungi | A note on the effect of submerged obstacles on water waves in a channel<br><br>Pub: J. Appl. Math. Phys., 32 756-763, 1981. |
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| 62. | J. B. Keller | Time-dependent queues<br><br>Pub: SIAM Rev., 24, 401-412, 1982. |
| 63. | R. E. Caflisch<br>B. Nicolaenko | Shock profile solutions of the Boltzmann equation<br><br>Sub: Comm. Math. Phys. |
| 64. | P. S. Hagan<br>R. E. Caflisch<br>J. B. Keller | Arrow's model of optimal pricing, use and exploration of undertain natural resources<br><br>Sub: Econometrica |
| 65. | R. E. Caflisch | Radiation transport in a hot plasma<br><br>Acc: SIAM J. Appl. Math., in press. |
| 66. | J. B. Keller<br>J.-M. Vanden-Broeck | Jets rising and falling under gravity<br><br>Acc: J. Fluid Mech., in press. |
| 67. | R. E. Caflisch | Fluid dynamics and the Boltzmann equation<br><br>Acc: Stud. Stat. Mech., in press. |
| 68.* | M. S. Falkovitz<br>M Seul<br>H. L. Frisch<br>H. M. McConnell | Theory of periodic structures in lipid bilayer membranes<br><br>Pub: Proc. Nat. Acad. Sci., 79, 3918, 1982. |
| 69. | R. E. Caflisch | The fluid-dynamic limit of a model Boltzmann equation in the presence of a shock<br><br>Pub: Institute National de Recherche en Informatique et en Automatique, INRIA No. 81, June 1981, 1-34. |
| 70. | P. F. Rhodes-Robinson | On the short surface waves due to half-immersed circular cylinder oscillating on water of infinite depth<br><br>Sub: |
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*Not supported by AFOSR or ONR.

72. P. F. Rhodes-Robinson — On the generation of surface waves at an inertial boundary

Sub:

73. R. E. Caflisch, G. C. Papanicolaou — Dynamic theory of suspensions with Brownian effects

Acc: SIAM J. Appl. Math., in press.

74. R. E. Caflisch, G. C. Papanicolaou — Instability in settling of suspensions due to Brownian effects

Acc: Proceedings o. [illegible]onference Two-Phase Flow.

75. R. E. Caflisch, B. Nicolaenko — Shock waves and the [illegible]tzmann equation

Acc: Proceedings N[illegible] conference non-linear PDE.

76. J. H. Maddocks — Restricted quadratic forms and their application to bifurcation and stability in constrained variational principles

Sub: SIAM J. Appl. Math.

77. M. S. Falkovitz, L. A. Segel — Spatially inhomogeneous polymerization in unstirred bulk

Acc: SIAM J. Appl. Math., in press.

78. M. S. Falkovitz, J. L. Frisch — The scale of non-homogeneity as defined by diffusion measurements

Pub: Journal of Membrane Science, 10, 61, 1982.

79. M. S. Falkovitz, H. L. Frisch, J. B. Keller — Optimal catalyst distribution in a membrane

Sub: Chem. Eng. Sci.

80.* M. S. Falkovitz, J. B. Keller — Crawling of Worms

Sub: J. Theor. Biol.

81. A. Jeffrey, J. Mvungi — The random choice method and the free-surface water profile after the collapse of a dam wall

Pub: Wave Motion, 4, 381-389, 1982.

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82. J. G. Watson
E. L. Reiss

A statistical theory for imperfect bifurcation

Pub: SIAM J. Appl. Math., 42, 135-148, 1982.

83. J. G. Watson
J. B. Keller

Acoustical scattering from rough surfaces

To be submitted.

84. M. I. Weinstein

Global existence for a generalized Korteweg - de Vries equation

Sub: SIAM J. Math. Anal.

85. M. I. Weinstein

Nonlinear Schrödinger equations and sharp interpolation estimates

Acc: Comm. Math. Phys.

86. M. Cheney

Two-dimensional scattering: the number of bound states from scattering data (a

Sub: J. of Math. Phys.

III. ABSTRACTS OF MANUSCRIPTS SUBMITTED SINCE MARCH 15, 1982.

✓1. Dynamic theory of suspensions with Brownian effects, by R. E. Caflisch and G. C. Papanicolaou.

We consider a suspension of particles in a fluid settling under the influence of gravity and dispersing by Brownian motion. A mathematical description is provided by the Stokes equations and a Fokker-Planck equation for the one-particle phase space density. This is a nonlinear system that depends on a number of parametric functions of the spatial concentration of the particles. These functions are known only empirically or for dilute suspensions. We analyze the system, its stability, its asymptotic behavior under different scalings and its validity from a more microscopic description.

2. Two-dimensional scattering: the number of bound states from scattering data, (a), by M. Cheney.

Relations are found between scattering data and the spectrum for the two-dimensional Schrödinger operator $\Delta+V(x)$, where V is a local noncentral potential. In particular a two-dimensional version of the Levinson theorem is obtained; this theorem gives the number of bound states in terms of the change in phase of the determinant of the scattering operator.

3. Shock profile solutions of the Boltzmann equation, by R. E. Caflisch and B. Nicolaenko.

Shock waves in gas dynamics can be described by the Euler Navier-Stokes, or Boltzmann equations. We prove the existence of shock profile solutions of the Boltzmann equation for shocks which are weak. The shock is written as a truncated expansion in powers of the shock strength, the first two terms of which come exactly from the Taylor tanh (x) profile for the Navier-Stokes solution. The full solution is found by a projection method like the Lyapunov-Schmidt method as a bifurcation from the constant state in which the bifurcation parameter is the difference between the speed of sound $c_0$ and the shock speed s.

4. Restricted quadratic forms and their application to bifurcation and stability in constrained variational principles, by J. H. Maddocks.

The subjects of this investigation are the abstract properties and applications of *restricted quadratic forms*. The first part of the presentation resolves the following question: if L is a self-adjoint linear operator mapping a Hilbert space $H$ into itself, and $S$ is a subspace of $H$, when is the quadratic form $\langle u,Lu \rangle$ positive for any non-zero $u \in S$? In the second part of the presentation, restricted quadratic forms are further examined in the specific context of constrained variational principles; and the general theory is applied to obtain information on stability and bifurcation. Two examples are then solved: one is finite-dimensional and of an illustrative nature; the other is a longstanding problem in elasticity concerning the stability of a buckled rod. In addition to being a valuable analytical tool for isoperimetric problems in the calculus of variations, the tests described are amenable to numerical treatment. A theorem concerning the variational characterization of eigenvalues is also obtained.

5. Spatially inhomogeneous polymerization in unstirred bulk, by M. S. Falkovitz and L. A. Segel.

A new experimental method for the formation of large polymers of very

narrow molecular weight distribution is examined theoretically. The problem belongs to the general class of transport-reaction problems in multi-component media. A comprehensive mathematical model of the phenomenon is presented. Noteworthy is the fact that diffusive fluxes are decomposed into two parts, pure diffusion and back-bulk-flow. It is shown that the full problem, which consists of an infinite number of coupled nonlinear differential equations, can be reduced to two such equations. Heat production is also considered in an auxiliary investigation. The appropriate differential equations are solved numerically and the physical significance of the results is discussed.

6. The scale of non-homogeneity as defined by diffusion measurements, by M. S. Falkovitz and H. L. Frisch.

The asymptotic behaviour of the permeation rate in non-homogeneous laminar slabs of increasing width $\ell$ is studied. We show rigorously that for a wide class of slabs with non-homogeneities distributed in a statistically homogeneous manner, the permeation rate approaches that of a homogeneous slab as $1/\ell^2$. The result is compared with previous studies of this subject.

7. Crawling of worms, by J. B. Keller and M. S. Falkovitz.

The mechanics of a worm crawling along a flat surface is analyzed. The external forces of friction and gravity, and the internal pressure and tension, are taken into account. An equation of motion is formulated, and solutions are sought in which both the tension and the linear density are required to lie between prescribed bounds. Pulse and periodic travelling wave solutions are constructed. The maximum crawling velocity is determined, as well as the wave form which achieves it. Comparison of the results with experimental observations shows that the theory yields a maximum crawling velocity which is much larger than the observed velocity. Therefore the theory was changed to require that the time rate of change of tension be less than a prescribed bound, rather than

that the tension be bounded. With this modification, the theory agrees fairly well with the observations.

8. <u>The random choice method and the free-surface water profile after the collapse of a dam wall</u>, by A. Jeffrey and J. Mvungi.

The random choice (RC) method due to Glimm [1], subsequently modified by Chorin [2] and Sod [3], is applied to the shallow water equations of Stoker [4], in order to determine the free-surface profile of water, as a function of position and time, when a dam wall suddenly collapses. The numerical results obtained by this method are compared with the analytical results due to Stoker for this classical problem [5], and with numerical results obtained by a further modification of the Glimm-Chorin scheme involving a smoothing operation. The improvement brought about by the smoothing, and the generally close agreement with the exact result that is then obtained, is a feature of this modified approach.

9. <u>A statistical theory for imperfect bifurcation</u>, by J. G. Watson and E. L. Reiss.

An "honest" statistical method is presented to analyze the effects of imperfections, and other disturbances on the bifurcation of solutions of non-linear problems. First, uniformly valid asymptotic approximations of the solutions are obtained for any realization of the imperfections. The approximations are valid as the magnitude of the imperfections approaches zero. The statistical properties of the solutions are then deduced directly from these approximations, for specified statistics of the imperfections. For simplicity of presentation, the imperfections are taken as zero-mean, wide-sense stationary, Gaussian random processes. The statistical analysis is elementary. It provides easily analyzed results for the expected values and variances of the solutions. Confidence limits are also given.

10. Global existence for a generalized Korteweg - de Vries equation, by M. Weinstein.

A sufficient condition for global existence is obtained for the generalized Korteweg - de Vries Equation (GKdV) $u_t + u^4 u_x + u_{xxx} = 0$ , $x \varepsilon R^1$ , $t \varepsilon R^+$ . This condition is expressed in terms of the solitary (traveling) wave solution of GKdV.

11. Nonlinear Schrödinger equations and sharp interpolation estimates, by M. I. Weinstein.

A sharp sufficient condition for global existence is obtained for the nonlinear Schrödinger equation

$$\text{(NLS)} \qquad 2i\phi_t + \Delta\phi + |\phi|^{2\sigma}\phi = 0 , \quad x \in \mathbb{R}^N, \quad t \in \mathbb{R}^+ ,$$

in the case $\sigma = 2/N$. This condition is in terms of an exact stationary solution (nonlinear ground state) of (NLS). It is derived by solving a variational problem to obtain the "best constant" for classical interpolation estimates of Nirenberg and Gagliardo.

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